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A-8-2 Tinv Scaling and Jg Reducing for nMOSFET with $HfSi_x/HfO_2$ Gate Stack by Interfacial Layer Formation Using Ozone Water Treatment Process

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Abstract

In this paper, we demonstrate a wet treatment process on $HfSi_x/HfO_2$ gate stack of nMOSFET fabricated with a gate last process in order to scale down the Tinv (electrical thickness at inversion state) value and reduce Jg (gate leakage). As a result, we succeed in scaling down Tinv to 1.41 nm without mobility and Jg degradations by using ozone-water-last treatment. we find that a high-density interfacial layer (IFL) is formed owing to ozone-water-last treatment, and Hf diffusion to IFL is suppressed, which has been analyzed by high-resolution angle-resolved spectroscopy.

Introduction

The main advantage of the Metal/High-k technology is the scalability of Tinv due to the elimination of gate depletion. However, there have been reports on degradation of electron mobility in thin Tinv region with Metal/High-k stacks [1]. We have reported that high electron mobility and low Jg at thin Tinv [2-5]. To achieve high electron mobility and low Jg in thinner Tinv region, the control of High-k/Si IFL is an important factor. It has been published from us that HfO_2/Si IFL thicknesses affect the electrical characteristics [6]. In this study, we developed a wet treatment process to improve the HfO_2/Si IFL quality. Thus, the further Tinv scaling and Jg suppression will be discussed.

Experiments

$HfSi_x/HfO_2$ nMOSFETs using a gate last process were fabricated (Fig.1). Three kinds of treatment process before depositing HfO_2 by ALD (Atomic Layer Deposition), namely SC2-last treatment, DHF-last treatment, and ozone-water-last treatment, were performed for samples preparation. ALD cycle case was fixed on A and B (cycle number A < B). After post deposition anneal (PDA) at 500 ^{o}C, $HfSi_x$ was deposited by PVD method. Samples for film analysis were extracted after and PDA, and then TEM (Transmission Electron Microscope) analysis was carried out to investigate the IFL thickness. Films were also analyzed by HR-ARS (high-resolution angle-resolved spectroscopy) using bright synchrotron radiation. This was done to investigate the depth profile using MEM (Maximum Entropy Method) analysis [7], and estimate IFL density [8].

Results and Discussion

First of all, electrical properties investigation was carried out. Fig.2 shows the Tinv as a function of ALD cycle case with various treatment processes. Tinv of the stack forming by SC2-last treatment is thinner than that by ozone-water-last treatment (Tinv=1.41nm). Besides, the stack of DHF-last treatment has the thinnest Tinv among the three different treatments. It suggested that IFL structure or HfO_2 thickness are different among the three treatments. Fig.3 shows the electron mobility as a function of the E_{eff} with three treatment processes. Although Tinv is thinner, electron mobility with IFL formed by ozone-water-last treatment is about the same value to that of SC2-last treatment, achieving to universal value. While the IFL formed by DHF-last treatment has the thinnest Tinv, degradation of electron mobility is observed. Fig.4 shows the Jg characteristics as a function of the Tinv under various treatment processes. Compared with SC2-last and ozone-water-last treatments, the stack formed by ozone-water-last treatment has lower Jg than that by SC2-last process, and the stack of DHF-last process has the lowest Jg among three treatment stacks. Fig.5 shows Jg-Ion characteristic of $HfSi_x/HfO_2$ with various last treatment processes. The stack formed by ozone-water-last treatment shows an improved behavior compared to that by SC2-last treatment on Jg-Ion characteristics in order to Jg reducing and Tinv scaling without mobility degradation.

Following investigation of electrical properties, film analysis was carried out. Fig.6 shows TEM images of HfO_2/IFL at the samples prepared with various wet last treatment processes, namely, (a) SC2-last, (b) DHF-last and (c) ozone-water-last. The most important point is that no IFL thickness varied with last treatment process (IFL thickness is about 1.1nm). For another point, we notice that HfO_2 thickness used by DHF-last process is thinner than that of other last processes. In this point, we think that incubation time of HfO_2 deposition is long on DHF-last treatment. Fig.7 shows the depth profiles of Hf, Si-oxide, Si-bulk, O atoms concentration obtained by MEM analysis. Hf 4f, Si 2pOxide, Si 2p bulk and O 1s spectra were detected by HR-ARS and using on MEM analysis. Fig.8 and Fig.9 show depth profiles of Hf or Si-oxide concentrations. It is revealed that the amount of Hf diffusion to IFL is the smallest on ozone-water-last treatment film (in Fig.8), and IFL thickness is the thinnest on DHF-last treatment film, thickest on SC2-last treatment film (in Fig.9). Table.1 summarized IFL density estimated from HR-ARS intensity with various last treatment processes. High density IFL is formed by ozone-water-last treatment. Fig.10 shows models of Hf diffusion to IFL for different last treatments. The film of SC2-last treatment is the thickest Tinv among three different treatments, because the IFL thickness is the thickest. Next, the film of ozone-water-last treatment has thinner IFL than that of SC2-last. Besides, the amount of Hf diffusion is the smallest among the three different treatments, due to IFL formed by ozone-water-last treatment has a high-density (Table.1). Finally, the film of DHF last treatment has the thinnest Tinv among the three different treatments, because the IFL and HfO_2 thickness is the thinnest. Then, the electron mobility degradation is shown and Hf diffusion is large. As these results, the most effective method to scale down Tinv and suppress Jg without mobility degradation is ozone-water-last treatment.

Conclusion

We have succeeded in scaling down the Tinv of nMOSFET to 1.41 nm without mobility degradation by used ozone-water-last treatment compared with SC2-last treatment on $HfSi_x/HfO_2$ gate stacks. And Jg was also suppressed by using ozone water last treatment. The cause of Tinv scaling without mobility degradation and Jg suppression was the reduced Hf diffusion due to high density interfacial layer formed by ozone-water last treatment.

Acknowledgements

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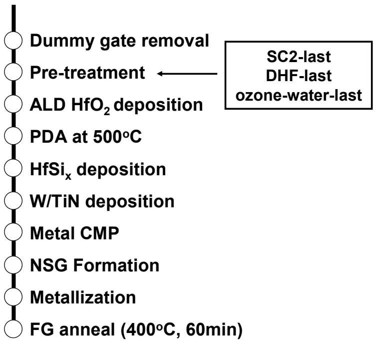


Fig.1 Process flow of $HfSi_x/HfO_2$ gate stack nMOSFETs fabricated with a gate last process, and samples for analysis used in this work.

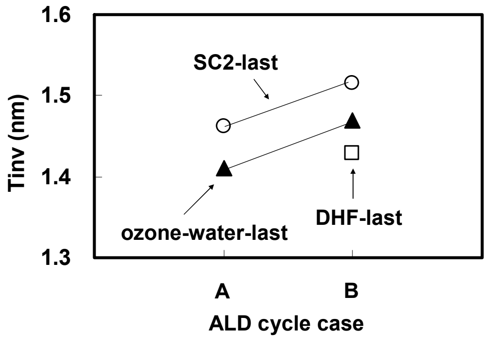


Fig.2 Tinv as a function of ALD cycle case under various interface treatments before HfO_2 deposition.

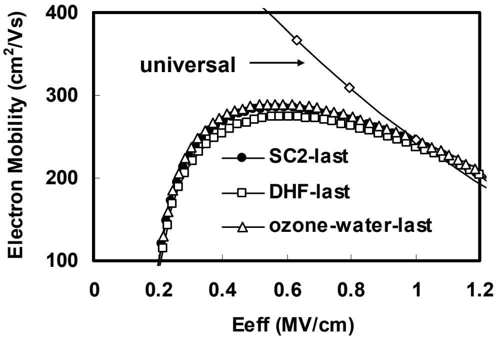


Fig.3 Mobility characteristics of $HfSi_x/HfO_2$ gate stack under various interface treatments before HfO_2 deposition

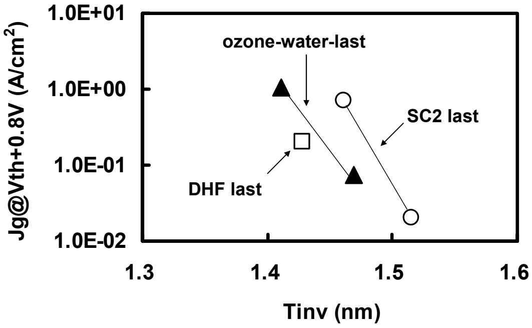


Fig.4 Tinv-Jg characteristics of $HfSi_x/HfO_2$ gate stack under various interface treatments before depositing HfO_2 .

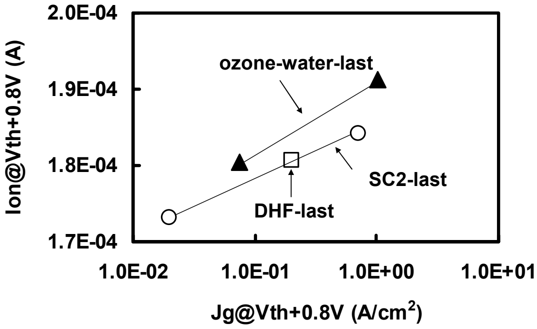
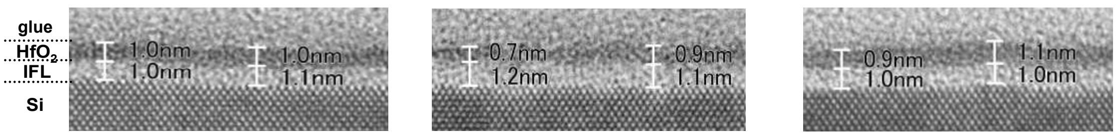


Fig.5 Jg-Ion characteristics of $HfSi_x/HfO_2$ gate stack under various interface treatments before depositing HfO_2.



(a) (b) (c)

Fig.6 TEM images with various interface treatment processes, namely (a) SC2-last, (b) DHF-last, and (c) ozone-water-last treatment.

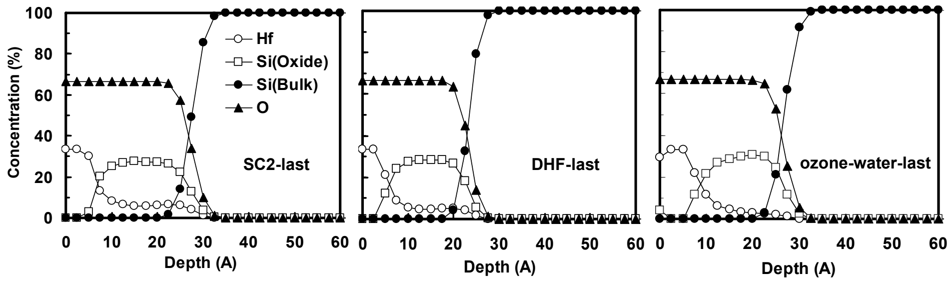


Fig.7 Comparison of depth profiles of Hf, Si-oxide, Si-bulk, and O atoms concentration obtained by MEM analysis under various interface treatment processes, SC2-last, DHF-last and ozone-water-last.

treatment	density (g/cm^3)
SC2-last	2.1
DHF-last	2.1
ozone-water-last	2.4

Table1 Comparison of IFL densities estimated from SR-XPS intensity for deferent interface treatment processes.

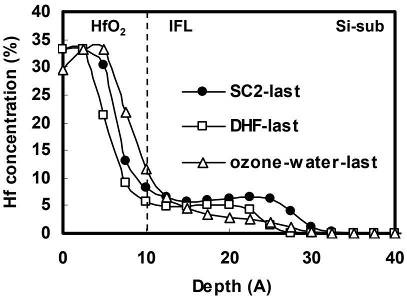


Fig.8 Depth profile of Hf concentration under various interface treatment process, SC2-last, DHF-last and ozone-water-last.

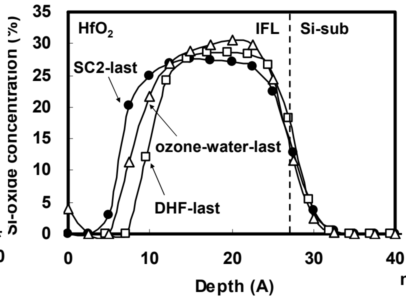


Fig.9 Depth profile of Si-oxide concentration under various interface treatment processes, SC2-last, DHF-last and ozone-water-last.

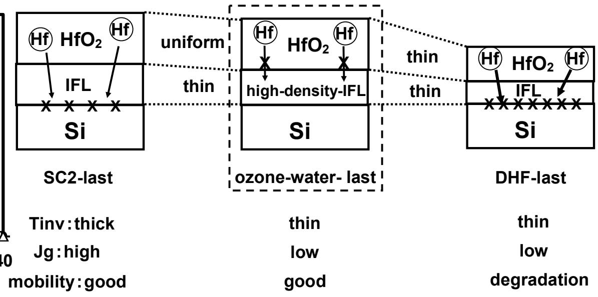


Fig. 10 Models of Hf diffusion to IFL for films used different interface treatments.